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Nutritional content of the African horned cucumber (*Cucumis metuliferus* E. May. Ex Naudin) fruit grown under varying fertiliser types and growing environments, and its potential role in human nutrition

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The fruit sector is one of the key role players in food and nutritional security by supplying vital nutrients, increasing food availability, promoting dietary diversity, and contributing to economic stability. Currently, most fruit species that contribute to food and nutritional supply in the fruit industry are exotic varieties such as mangoes, oranges, grapes, and English cucumbers, owing to the established and reputable literature on their agronomic practices and protocols. To achieve food and nutritional security globally, the introduction of indigenous fruit crops, especially in regions where they are native, appear to be a promising strategy that could accelerate the attainment of Sustainable Development Goal 2 (Zero Hunger). Additionally, this inclusion may assist in complementing existing commercial crops to substantially boost communal nutrition and food diversity by offering phytochemicals, nutrients, and minerals, which are vital for sustained health and wellness. Among such crops is the African horned cucumber (*Cucumis metuliferus* E. May. Ex Naudin), an indigenous fruit crop of Southern Africa claimed to be nutrient dense due to its abundance of vitamins and minerals, which human beings require in smaller and larger quantities daily. However, literature on the fruit's biochemical content response when subjected to differing growing environments and the use of specific fertiliser types appears to be scanty. Therefore, the current study evaluated the impact of differing growing environments (greenhouse and shade net) and fertiliser types (organic and inorganic/chemical) on the biochemical constituents of African horned cucumber fruit. In addition, the fruit nutritional content was compared with the average recommended daily intake to determine its potential contribution to human health and

nutrition. The results showed that a treatment combination of shade net and chemical fertilisers increased phosphorus (577.7 mg/100g DW) and potassium (1074 mg/100g DW) compared to other treatments. As a result, growers are encouraged to consider the greenhouse environment combined with chemical fertilisers for maximising phytochemicals such as total phenols and vitamin C, whereas the treatment combination of shade net and chemical fertiliser appeared to be the best for maximising minerals such as calcium, phosphorus, and iron.

KEYWORDS

food security, micro-minerals, potential commercialisation, Sustainable Development Goal 2, underutilised crops

1 Introduction

Sustainable Development Goal (SDG) 2, through the Zero Hunger Initiative, is a significant focus of the United Nations 2030 Agenda (Gilani et al., 2023). The agricultural sector has been identified as one of the critical key role players in efforts to accomplishing these SDGs (Veldhuizen et al., 2020). Various scholars, such as Dorward (2013), have reported rising food prices, over-dependence on exotic crops and climate change, among other factors, as the main causes of food and nutritional insecurity in societies. One of the promising strategies that could be adopted to accelerate the attainment of the Zero Hunger Initiative (SDG 2) is mainstreaming indigenous fruits into the dominant food system and making them more accessible and consumed by a wider population. Indigenous fruits are defined as crops that grow naturally in the wild without the constant supply of agricultural inputs such as irrigation and fertilisers (Hiywotu, 2025). These fruit crops are native to their respective regions and could assist in minimising the over-reliance on exotic crops that require constant application of irrigation, fertilisers, and pesticides to achieve yield returns (Janbandhu et al., 2024). The African horned cucumber (*Cucumis metuliferus* E. Mey. ex Naudin) is an annual climbing plant that grows naturally in the wild and is indigenous to various regions of Southern Africa with warm climates – Figure 1 (Maluleke et al., 2021). The benefits of the African horned cucumber fruit have been reported by Lekoba et al. (2024) as being (i) rich in vitamins, (ii) rich in antioxidants and (iii) low in calories, which is essential for people relying on specific foods for body weight management. Despite its abundance of various biochemical constituents, the fruit remains underutilised due to limited literature on its response to growing environments and fertiliser application, which directly affects its nutrient content and contribution to human health. Therefore, the establishment of a credible scientific protocol on how the crops respond to varying cultivation environments and fertiliser types will directly support global food diversity. As a result, the current study investigated the combined effect of different growing environments (greenhouse and shade net) and fertiliser types (organic and inorganic) on the biochemical constituents of the African horned cucumber fruit, with the goal of determining the best treatment combination for producing nutrient-dense fruits. The biochemical constituents of the fruit were compared to the average recommended daily intake (ARDI) to assess the fruit's potential contribution to human health and nutrition, thereby facilitating its commercialisation towards achieving SDG2 (Zero Hunger).

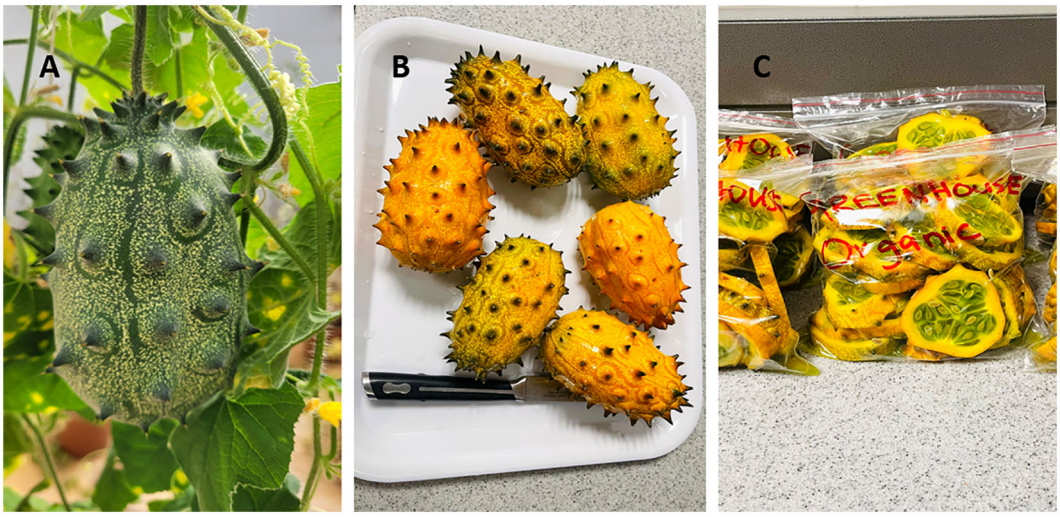


FIGURE 1
African horned cucumber fruit. **(A)** = fruit on the growing plant. **(B)** = ripe harvested fruit. **(C)** = ripe cut fruits. (Authors' own).

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TABLE 1 Meteorological data of shade net and open space environments.

Month	Tmax (°C)	Tmin (°C)	AMT	Light intensity
Greenhouse				
September	28	18	23	935
October	28	18	23	958
November	28	18	23	1112
December	28	18	23	1233
January	28	18	23	1230
	28	**18**	**23**	**1093.6**
Shade net				
September	28	16	22	989
October	30	18	24	1155
November	31	17	24	1652
December	32	17	24,5	1711
January	33	18	25,5	1756
	30.8	**17.2**	**24**	**1452.6**

Tmax, maximum temperature; Tmin, minimum temperature; °C, degree Celsius; AMT, average monthly temperature.
Value in bold represents: maximum temperatures, minimum temperature, average mean temperature and light intensity.

TABLE 2 Different fertiliser types used for the experimental treatments. .

Organic fertiliser	Ratio	NPK content per treatment	Total application of elements (mg/g of soil)
Nitrogen (N) = 3	6	7.2	1.44
Phosphorus (P) = 2	4	4.8	0.96
Potassium (K) = 5	10	12	2.4
Total = 20%			
Chemical fertiliser	**Ratio**	**Mineral concentration**	**Total application of elements (mg/g of soil)**
Nitrogen (N) = 2	4.9	5.8	1.16
Phosphorus (P) = 3	7.3	8.8	1.76
Potassium (K) = 2	4.9	5.8	1.76
Total = 17%			

mg, milligram; g, gram.

2 Materials and methods

This study was undertaken at the Florida Science Campus of the University of South Africa (Unisa) (26° 10' 30"S, 27° 55' 22.8"E) during the 2024 to 2025 planting seasons under two growing conditions – greenhouse-controlled average temperature (16–28 °C) and shade net (18–30.8 °C) – as illustrated in Table 1. Healthy and certified seeds of the African horned cucumber (*C. metuliferus* E. May. Ex Naudin) were sourced from Seeds for Africa (Pty) Ltd, located in Cape Town in South Africa. Seedlings, germinated from coconut coir substrate with uniform height and width after 30 days, were transferred into containers measuring 30 cm in depth and 30 cm in breadth, filled with loam soil sourced from Culterra (Pty) Ltd, located in the Johannesburg region (Equation 1). In accordance with the methodology of Maluleke and Thobejane (2025), the investigation was conducted as a 2 x 3 factorial experiment set in a completely randomised design featuring six treatments, each repeated six times. Following the establishment of seedlings, plants received 5 g of differing types of granule fertilisers: (i) organic fertiliser (GuanoBoost, Pretoria, South Africa) containing nitrogen (N), phosphorus (P), and potassium (K) in the ratios [N-3, P-2, K-5], and (ii) inorganic/chemical fertiliser (Nitrogreen KAN/LAN, Protek, Pretoria, South Africa) with nitrogen (N), phosphorus (P), and potassium (K) in the ratios [N-2, P-3, K-2] across three growth conditions (greenhouse and shade net) (Table 2). The pots were positioned 1.2 m apart, and vertical trellising was used to support the plants. Only fully mature, well-developed, non-fallen ripe fruits were harvested for biochemical content analysis according to the procedure outlined by Moyo et al. (2018). The fruit colour chart created by Tuckeldoe et al. (2023) served as a reference for assessing the fruit's maturity.

$$\text{Area (depth} \times \text{width)} 30 \quad \text{cm} \times 30 \quad \text{cm} = 900 \quad \text{cm}^2, \quad A = \pi\left(\frac{d}{2}\right) \times 2 \quad \text{d} = 286.5 \quad \text{cm}^2 \text{ planting plots} \tag{1}$$

2.1 Soil mineral analysis

The soil mineral analysis, as depicted in Table 3, was conducted at the Agricultural Research Council (25° 44' 19.4" S 28° 12' 26.4" E) in Arcadia, Pretoria. The ethical clearance for the study was approved by the Unisa College of Agriculture and Environmental Science Research and Higher Degree Committee (ethical clearance reference: 2022/CAES_HREC/104).

2.2 Sample preparation

The harvested fruits were transported to the laboratory on the Unisa Florida Science Campus. Upon arrival, the fruits were manually sorted for consistency in colour, size, shape, and flaws, then disinfected by washing with a 0.02% sodium hypochlorite (NaClO) solution for one minute. Following the cleaning, fruits were sliced using a sharp sterilised knife to separate the pulp from the seeds. Fruit pulps were subjected to freezing at −80 °C for two days before undergoing freeze-drying. A freeze dryer (VirTis Co., Gardiner, NY, USA) was utilised to lyophilise fruit pulps, maintaining a condenser temperature of −88.7 °C and a vacuum pressure of 7 mTorr. The samples were then grounded using a mortar and pestle and stored for later analysis.

2.3 Determination of biochemical and mineral constituent analysis

The biochemical composition of the African horned cucumber fruit, harvested from plants cultivated under various fertiliser types (organic and inorganic/chemical) and environments (greenhouse and shade net), was analysed using freeze-dried samples. The vitamin C content was quantified in milligrams per hundred grams of dry weight (mg/100g DW) using the method outlined by (Amaral et al., 2005), as adopted by Moyo et al. (2018) and Maluleke et al. (2024), with minor modifications (triplicates). The measurement of vitamin E in mg/100g DW was conducted using

TABLE 3 Mineral analysis (mg.kg^{-1}) of experimental soil for *C. metuliferus* experiment.

Mineral composition analysis (mg.kg^{-1})								
Fe	Mn	Cu	Zn	P	Ca	Mg	K	Na
35	19	12	18	22	1 421	218	215	45

mg, milligram; g, gram.

the procedure outlined by (Santos-Zea et al., 2011), as used by (Maluleke and Thobejane, 2025), with minor adjustments (triplicates). Regarding the total flavonoids content, quantified in catechin equivalent milligrams per hundred grams of dry weight (CE mg/100g DW) using the method of (Baba and Malik, 2015), as modified by (Samanta et al., 2011), was used with minor adjustments (triplicates). The total phenolic content, measured in gallic acid equivalents in milligrams per hundred grams of dry weight (GAE mg/100g DW), was determined using the method outlined by (Moyo et al., 2018), with minor modifications (triplication). The macro and micro mineral content, measured in mg/100g DW, was determined using the method from (Moyo et al., 2018), adopted by (Samanta et al., 2011), with some modifications (triplicates).

2.4 Determining the ARDI

To evaluate the possible dietary benefits of African horned cucumber fruit, the concentration of each nutrient (measured per 100 g of fresh weight) was evaluated against documented nutritional standards. ARDI metrics were computed based on internationally accepted dietary reference standards for distinct population segments and were used exclusively as a comparative reference to evaluate the percentage contribution of a 100 g serving of African horned fruit to daily nutrient demands (Maluleke et al., 2024).

ARDI formula:

ARDI = (Sum of all values)/(Number of values) = Equation 1

The percentage contribution was calculated using Equation 2:

$$\text{Percentage contribution}(\%) = (\text{Nutrient concentration per 100 g} \div \text{ARDI}) \times 100 \quad (2)$$

The ARDI values presented in Table 4 are intended for comparative purposes only and should not be interpreted as recommended dietary allowances for any specific population group.

3 Statistical analysis.

A two-way analysis of variance (ANOVA) was used to evaluate the combined effects of independent variables, namely (i) types of fertiliser (organic and inorganic/chemical) and growing environments (greenhouse and shade net), on the dependent variables, which encompassed biochemical constituents (vitamin C, vitamin E, total phenols, total flavonoids, and macro- and micro-minerals) of the African horned cucumber. All the variables were subjected to fundamental statistical analyses such as least significant difference (LSD), grand mean, and standard deviation. Statistica (USA) version 10 was used for all the statistical work.

TABLE 4 Average recommended daily (mg) intake of phytochemicals and minerals.

Phytochemical/ Mineral	ARDI	Reference
Beta-carotene	4.5	NIH 2026a
Calcium	1100.0	NIH 2026b
Copper	1.1	NIH 2026c
Iron	15.2	NIH 2026d
Magnesium	363.0	MHA 2026
Phosphorus	369.8	NIH 2026e
Total flavonoids	750.0	Lekoba et al., 2024 & Cheok and Rodriguez-Mateos, 2026
Total phenols	959.0	Del Bo' et al., 2019 & WebMD, 2026
Vitamin C	92.5	NIH 2026e
Zinc	9.1	Lekoba et al., 2024; NIH 2026f

ARDI, average recommended daily intake; NIH, National Institutes of Health; AHA, American Heart Association.

3.1 Correlation analysis

In accordance with the method followed by (Lekhuleni and Maluleke, 2025), the relationships among various biochemical constituents (total flavonoids, total phenols, beta-carotene, vitamin C, and vitamin E) and macronutrients (calcium, sodium, phosphorus, magnesium, and potassium) and micronutrients (copper, iron, molybdenum, and zinc) were assessed using a correlation matrix with the help of Statistica version 12 (StatSoft Inc., Tulsa, OK, USA). Pairwise correlation analyses were conducted using *C. metuliferus* samples grown under greenhouse and shade net environmental conditions. The *C. metuliferus* plants under these conditions were fertilised with either chemical or organic fertilisers. The correlation results are presented in Tables 1-4, with $p < 0.05$ and 0.01 for very strongly positive and negative variables respectively. The full coefficients and corresponding nodal networks are presented in Figures 1-4.

4 Results and discussion

4.1 Biochemical constituents

Table 5 presents the biochemical contents (total flavonoids, total phenols, vitamin C, and vitamin E) of the African horned cucumber fruit cultivated under different fertiliser types (organic and inorganic/chemical) and conditions (greenhouse and shade net). The study found considerable ($P \leq 0.05$) variance among the treatments. The study showed that the total flavonoid ranged between 0.28 and 0.58 CE mg/100g DW. Furthermore, the results demonstrated that the combination of greenhouse treatment and control (without fertilisers) decreased total flavonoid content from 0.58 to 0.28 CE mg/100g DW, while the combination of greenhouse environment and chemical fertiliser raised it from 0.28 to 0.58 CE mg/100g DW. It has been established that flavonoids are biological molecules that significantly contribute to plant growth and

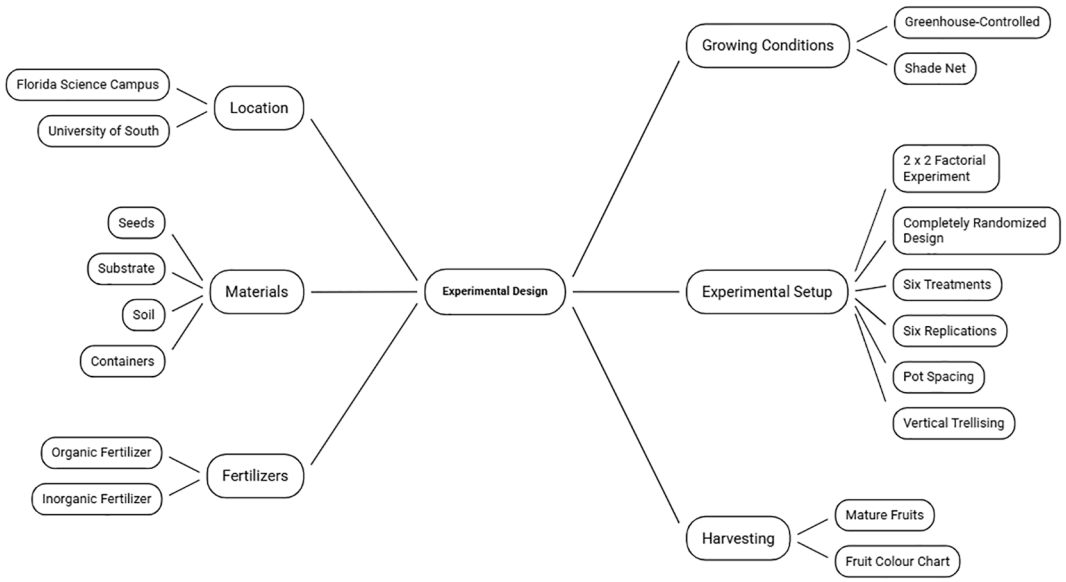


FIGURE 2
Experimental design for African horned cucumber fruit.

development, affecting different processes and safeguarding plants from environmental stress (Deng et al., 2019; Makoi and Ndakidemi, 2011).

In this study, the variation between the temperature in the greenhouse (28 °C) and in the shade net (30.8 °C) was 2.8 °C, while the nitrogen content ratio between the greenhouse (6) and shade net (4.9) varied by 1.1%. The integration of a greenhouse temperature of 28 °C, considered optimal, along with a balanced nitrogen ratio, might have led the plant to transition from vegetative growth, normally influenced by primary metabolites, to the production of phytochemicals like flavonoids, through the enzymatic action of phenylalanine ammonia-lyase, which is essential for linking and transitioning primary metabolism to secondary metabolism; hence, this treatment accumulated a greater flavonoid content compared to the control plants (no fertiliser treatment), which appeared to have lower flavonoid content despite the plants being in an identical growing environment. These discoveries are consistent with the conclusion reported by Pott et al. (2019) and Ali et al. (2021), who highlighted that the levels of phytochemicals in fruits are directly affected by their environmental conditions.

Total flavonoids, predominantly present in plant-based goods like fruits, are crucial in human health and nutrition, as they confer

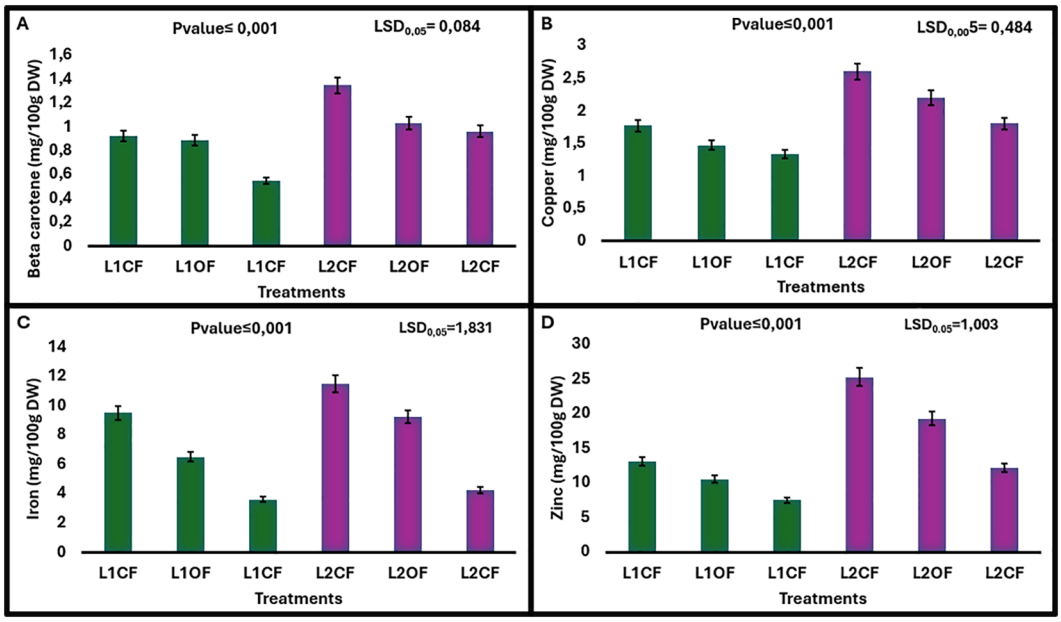


FIGURE 3
Micro-mineral content of the African horned cucumber grown under varying growing environments and fertilisers: CF, chemical fertiliser; OF, organic fertiliser; C, control (without fertiliser); L1, Greenhouse; L2, Shade net. LSD represents the least significant difference. **(A)** Beta carotene, **(B)** Copper, **(C)** Iron and **(D)** Zinc.

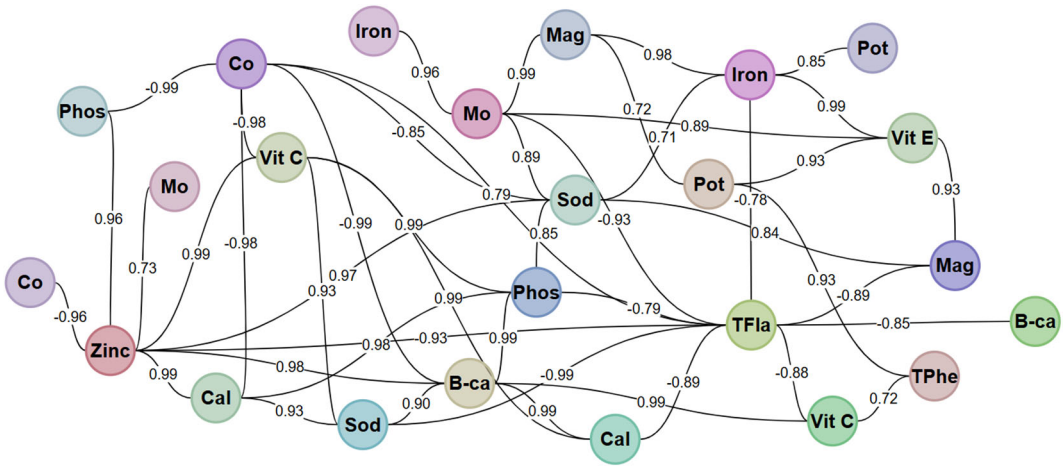


FIGURE 4
Total Flavonoids vs Beta-carotene, Vitamin C, Calcium, Sodium, Phosphorus, Magnesium, Copper, Iron, Molybdenum, Zinc; Total Phenols vs Vitamin C, Potassium; Beta-carotene vs Vitamin C, Calcium, Sodium, Phosphorus, Copper, Zinc; Vitamin C vs Calcium, Sodium, Phosphorus, Copper, Zinc; Vitamin E vs Magnesium, Potassium, Iron, Molybdenum; Calcium vs Sodium, Phosphorus, Copper, Zinc; Sodium vs Phosphorus, Magnesium, Copper, Iron, Molybdenum, Zinc; Phosphorus vs Copper, Zinc; Magnesium vs Potassium, Iron, Molybdenum; Potassium vs Iron; Copper vs Zinc; Iron vs Molybdenum; Molybdenum vs Zinc.

numerous health benefits, including a reduced risk of chronic diseases owing to their anti-inflammatory properties (Oluwole et al., 2022). The disparity between the superior total flavonoid content of the African horned cucumber (0.58), cultivated in a greenhouse with chemical fertiliser treatment, and the average recommended daily consumption (750 mg) is 749.4 mg. This suggests that the African horned cucumber fruit cultivated under the combined treatment conditions of a greenhouse environment and chemical fertiliser may potentially provide around 0.07% of the daily flavonoid requirement for human beings. Despite the low content derived from this study, consumption of the African horned cucumber fruit may potentially aid in the prevention of conditions such as cardiovascular diseases and some cancer-related ailments, both of which are associated with a low flavonoid content in the human diet (Vashisth et al., 2017).

Regarding total phenolic content, the observed trend illustrates that fruits grown in a greenhouse environment have super total phenolic content compared to those of other treatments. Moreover, the findings indicate that the values varied from 2.8 to 39.5 GAE mg/100g DW. The results also indicate that the combination of shade net environment and organic fertiliser decreased the total phenolic content from 39.5 to 2.8 GAE mg/100g DW, but the combination of greenhouse environment and chemical fertiliser raised it from 2.8 to 39.5 GAE mg/100g DW. Temperature has a considerable impact on the phenolic content of fruits because it influences the enzymic activities involved in their biosynthesis (Tolic et al., 2017).

In this study, the temperature difference between the greenhouse (28 °C) and the shade net environment (30.8) was 2.8°, while the nitrogen ratio difference between the chemical fertiliser (7.2) and the organic fertiliser (5.8) was 1.3%. The observed effect could be ascribed to the combination of an ideal temperature of 28 °C for cucumber crops with moderate nitrogen levels in the soil, which promotes the enzymatic function of phenylalanine ammonia-lyase,

TABLE 5 Biochemical constituents of the African horned cucumber fruit grown under varying fertilisers and environments.

Treatment	Total flavonoids (CE mg/100g DW)	Total phenols (GAE mg/100g DW)	Vitamin C (mg/100g DW)	Vitamin E (mg/1 000g DW)
L1CF	0.58 (0.6)	39.5(5.4)	67.8(4.6)	46.9(1.3)
L1OF	0.43(0.1)	24.3(2.3)	33.6(2.4)	41.3(3.8)
L1C	0.28(0.2)	3.8(1.3)	26.5(1.9)	33.8(2.6)
L2CF	0.29(0.3)	4.3(2.4)	45.6(4.4)	35.4(3.3)
L2OF	0.35(0.1)	2.8(1.2)	30.1(3.2)	28.8(2.1)
L2C	0.31(0.2)	3.9(2.3)	28.4(2.4)	10.8(1.4)
Grand mean	0.377	13.1	38.7	32.8
LSD 0.05	0.085	0.281	3.518	4.938
P value	**0.001**	**0.001**	**0.001**	**0.001**

L1CF, Location 1 (greenhouse) chemical fertiliser; L1OF, Location 1 (greenhouse) organic fertiliser; L1C, Location 1 greenhouse) control; L2CF, Location 2 (shade net) chemical fertiliser; L2OF, Location 2 (shade net) organic fertiliser; L2C, Location 2 (shade net) control. The standard deviations of the mean are shown by numbers enclosed in brackets. Lower than 0.05 P values are in bold. In terms of mean difference, LSD0.05 is the least significant.

converting phenylalanine into phenolic precursors and yielding superior fruit content, in contrast to those grown in a shade net environment at 30 °C with organic fertiliser, where higher temperatures may have caused thermal degradation, breaking ester and glycosidic bonds and leading to a reduction in the overall phenolic content of the fruits. These findings are consistent with those of (Wang et al., 2024), who reported a substantial decline in the total phenolic content of apples and strawberry cultivated under elevated temperatures.

Within human health and nutrition, phenols are natural substances found in fruits; they function as effective antioxidants and cellular regulators responsible for shielding the human body from chronic conditions such as cardiovascular disease and cancer (Valdés et al., 2015). The difference between the maximum total phenolic content of the African horned cucumber (39.5 mg), cultivated under the treatment combination of greenhouse climate and chemical fertiliser, and the average recommended daily consumption (959 mg) was 919.5 mg. This indicates that the African horned cucumber fruit cultivated under the combined treatment of greenhouse conditions and chemical fertiliser may potentially contribute approximately 4.1% of the daily total phenols required by human beings. Although the values derived from this study are below the recommended daily intake, the consumption of African horned cucumber fruit cultivated under the combination of greenhouse conditions and chemical fertilisers may potentially help to mitigate conditions such as diabetes and cardiovascular diseases, which are linked to low phenolic content in the human diet (Kasprzak-Drozd et al., 2021).

Concerning vitamin C content, the results showed that it ranged from 26.5 to 67.8 mg/100g DW. Furthermore, the results revealed that the treatment combination of shade net and organic fertiliser lowered vitamin C content from 67.8 to 26.5 mg/100g DW, but the treatment combination of greenhouse and chemical fertiliser raised it from 26.5 to 67.5 mg/100g. The interplay of temperature and soil nutrient conditions has been shown to directly influence the vitamin C content of fruits (Foyer and Noctor, 2011; Fenech et al., 2019).

This investigation revealed a temperature differential of 2.8 °C between the maximum temperature of the greenhouse (28 °C) and that of the shade net environment (30.8 °C), while the nitrogen ratio between organic (7.2%) and chemical (4.9%) fertilisers was 2.3%. The combination of a greenhouse environment with a maximum temperature of 28 °C and a nitrogen-rich chemical fertiliser at a ratio of 4.9 significantly contributed to the elevation of vitamin C concentrations in the African horned cucumber fruit. These conditions may have directly influenced the superior efficacy of stomatal conductance and the biosynthetic enzyme galactose phosphorylase, which functions optimally in cucumber plants cultivated at an ideal temperature of 28 °C combined with good soil nutrition, as opposed to the shaded net environment (30 °C) combined with control (no fertiliser), which could impede the enzymic activities and poor gaseous exchange due to stomatal closure, resulting in diminished content due to degradative stress, possibly triggered by elevated temperatures and insufficient soil nutrients; thus, there was lower content under this treatment combination compared to others. These discoveries are consistent with the findings of (Gruda et al., 2025), who noted that alterations in temperature directly affected the vitamin C concentration in most horticultural crops.

In human health and nutrition, vitamin C has a crucial function as an antioxidant, safeguarding cells from damage inflicted by free radicals generated during food metabolism (Delanghe et al., 2011). Moreover, it is an essential nutrient that significantly contributes to tissue healing, immunological function, iron absorption, and the formation of blood vessels and bones (Carr and Rowe, 2020). In this study, the difference between the maximum vitamin C (67.8) found in African horned cucumber fruit grown using a combination of greenhouse and chemical fertilisers and the average recommended daily consumption (92.5 mg) was 13.5 mg. This suggests that the African horned cucumber fruit grown in a greenhouse environment with chemical fertiliser may potentially contribute around 73.2% of the vitamin C necessary for human beings daily. Furthermore, the findings of this study suggest that the consumption of the African horned cucumber fruit cultivated under the combined conditions of greenhouse and chemical fertiliser may help to alleviate issues such as chronic fatigue, poor wound healing, gingival bleeding, and loose teeth – all of which are indicative of insufficient vitamin C levels in the human diet (Achaglinkame et al., 2019; Miret and Munné-Bosch, 2015).

Regarding vitamin E, the research findings indicate a range of 10.8 to 46.9 mg/100g DW. Furthermore, the results demonstrate that the combination of shade net treatment and control (without fertilisers) decreased the vitamin E content from 46.9 to 10.8 mg/100g DW, but the combination of greenhouse environment and chemical fertiliser elevated it from 10.8 to 46.9 mg/100g DW. In plant physiology, the chloroplast is known for its critical function in the accumulation of metabolic components such as vitamin E (Fatima et al., 2025). Excessive conditions, such as high and low temperatures, have a negative impact on this vitamin because they alter enzymic activity (Lee and Han, 2018).

For this study, the difference in the maximum temperature of the greenhouse (28 °C) and that of the shade net (30.8 °C) was 2.8 °C. Consequently, the treatment involving a greenhouse environment at 28 °C and nitrogen-rich fertiliser likely contributed to an enhancement in vitamin E levels, as these conditions facilitate chloroplast opening, thereby enabling plants to optimise their net photosynthetic rate due to the ample availability of metabolic precursors, in contrast to those cultivated under shade nets at 30.8 °C without fertiliser, which diminishes the plants' capacity to accumulate vitamin E due to compromised physiological functions like stomatal closure, resulting from high temperatures and inadequate soil nutrition. Findings of this study correspond with those of (Niu et al., 2022), who connected the accumulation of vitamin E in plants to their growing environments.

In human nutrition and health, vitamin E is essential because it functions primarily as an antioxidant (Khallouki et al., 2020). Additionally, it safeguards cells from free-radical-induced damage, bolsters the immune system, and facilitates red blood cell production (Schneider, 2005). It also contributes to the prevention of chronic diseases linked to free radicals, and it participates in numerous physiological activities, including cell communication and gene expression (Rizvi et al., 2014). According to the study's

TABLE 6 Macro-mineral (mg/100g DW) of the African horned cucumber (*C. metuliferus)* grown under different fertilisers and environments.

Treatment	Calcium	Magnesium	Phosphorus
L1CF	27.2(0.1)	332.3(77)	516.7(28)
L1OF	23.8(0.3)	460.7(29)	308(13)
L1C	19.1(0.5)	178(23)	256.7(11)
L2CF	31.8(2.1)	448(10.)	573.7(51)
L2OF	26.3(0.8)	397.3(32)	300(53)
L2C	23.4(0.3)	155(40)	175(63)
Grand mean	25.3	328.6	355
LSD 0.05	1.599	74.9	76.75
P value	**0.01**	**0.01**	**0.05**

L1CF, Location 1 (greenhouse) chemical fertiliser; L1OF, Location 1 (greenhouse) organic fertiliser; L1C, Location 1 (greenhouse) control; L2CF, Location 2 (shade net) chemical fertiliser; L2OF, Location 2 (shade net) organic fertiliser; L2C, Location 2 (shade net) control. The standard deviations of the mean are shown by numbers enclosed in brackets. Lower than 0.05 P values are in bold. In terms of mean difference,LSD0.05 is the least significant.

findings, the African horned cucumber fruit cultivated under a combination of greenhouse and chemical fertiliser had the highest vitamin C content (46.9), which differed from the average daily recommended intake (15) by 31 mg. The findings of this study indicate that African horned cucumber fruit cultivated using a combination of greenhouse conditions and chemical fertiliser may provide three times the daily recommended intake of vitamin E for human nutrition. Moreover, research findings indicate that the consumption of the African horned cucumber fruit may mitigate conditions such as muscular weakness, impaired chemical coordination, diminished vision, and neurological dysfunction, all of which are symptoms linked to insufficient vitamin E intake in human nutrition (Montanaro et al., 2006; Hocking et al., 2016).

4.2 Macro-minerals

Table 6 shows the macro-mineral content (calcium, phosphorus, and magnesium) of African horned cucumber fruit harvested from soil treated with varying fertiliser types (chemical and organic) under differing environments (greenhouse and shade net). The study revealed a significant difference ($P \leq 0.05$) in the phosphorus, calcium, and magnesium levels. In respect of the calcium content, the study's results evinced the range as between 19.1 to 31.8 mg/100g DW. Additionally, the study showed that the calcium level decreased from 31.8 to 19.1 mg/100g DW when the greenhouse conditions combined with a control treatment (no fertiliser) were used, but it increased from 19.1 to 31.8 mg/100g DW when the shade net environment was used in combination with chemical fertiliser. It has been widely demonstrated that the accumulation of calcium in fruits during growth is significantly influenced by environmental factors, including temperature and light intensity (Kanski et al., 2021; Beto, 2015). Elevated temperatures and light intensity have been demonstrated to enhance calcium absorption in various plant species; however, the impact differs among crops (Kanski et al., 2021).

For this study, the variation between the maximum temperature of the greenhouse (28 °C) and that of the shade net (30.8 °C) was 2.8 °C, while the light intensity between greenhouse (1093.3) and shade net (1452.6) was 359.3 lux. The elevated evapotranspiration driven by the greater water and nutrient demands of plants in a shade net environment (30.8 °C) due to higher temperatures was likely responsible for the increased calcium content in the fruit, in contrast to those cultivated in a greenhouse at 28 °C, where the consistent temperature may have led to a reduced transpiration rate, thus yielding to lower calcium content in the fruits grown under these treatments (greenhouse and control-no fertilisers). Findings of this investigation correspond with those of (Montanaro et al., 2015), who found that the accumulation of calcium in fruits was directly associated with environmental variables, such as transpiration rates influenced by surrounding temperatures.

For human health and nutrition, calcium is an important mineral for general health, especially for keeping bones and teeth healthy, muscles contracting, neurons functioning, blood clotting, and maintaining normal heartbeat (Kumssa et al., 2015). In addition to its structural role, calcium is involved in other physiological activities, including blood pressure regulation and nerve transmission (Shlisky et al., 2022). The disparity between the highest calcium content (31.8 mg) found in the African horned cucumber fruit, cultivated under the treatment combination of shade net and chemical fertiliser, and the average required daily consumption (1100 mg) was 1068.2 mg. This suggests that the fruit of African horned cucumbers grown using a shade net and chemical fertiliser may provide roughly 2.9% of the daily calcium that human beings need. Despite the values being lower than the recommended daily intake for human beings, consumption of the African horned cucumber fruit may potentially aid in the prevention of conditions such as muscle cramps, weak bones, and abnormal heartbeat, all of which are symptoms linked to inadequate calcium intake in human health and nutrition (Lekhuleni et al., 2024; Gerendás and Führs, 2013).

In respect of magnesium content, the level varied between 155 and 460 mg/100g DW, according to the results. Furthermore, the study's findings show that while the magnesium content increased from 155 to 460 mg/100g DW when plants were grown under the treatment combination of the greenhouse and organic fertiliser, it decreased from 460 to 155 mg/100g DW under the combination of shade net and control (without fertiliser). It has been well established that temperature, when paired with soil fertility status, has a substantial impact on the accumulation of magnesium content in fruits throughout growth (Nielsen et al., 2015).

In this study, the variation between the maximum temperature of the greenhouse (28 °C) and that of the shade net (30.8 °C) was 2.8 °C. The combination of organic fertiliser and optimal temperature seems to have improved the magnesium uptake in plants, as organic fertilisers bind this mineral and release it over time, whereas the shade net environment at 30.8 °C without fertilisers may have led to diminished magnesium levels in plants due to elevated temperatures potentially depleting soil magnesium without replenishment from increased evapotranspiration; hence, there was lower content in fruits grown under this treatment combination when compared to others. These discoveries align with the results of (Caruso et al., 2019), who reported varying magnesium levels in tomato fruit grown under varying fertiliser types.

In human health and nutrition, magnesium is essential for numerous facets, including serving as a vital mineral for muscle and

neuron function, energy metabolism, and skeletal integrity (De Baaij et al., 2015). It participates in more than 300 metabolic activities, facilitating processes such as blood pressure regulation, blood sugar management, protein synthesis, and DNA repair (Fiorentini et al., 2021). The difference between the maximum magnesium content (460 mg), derived from fruits cultivated in a greenhouse with organic fertiliser, and the average required daily consumption (363 mg) is 97 mg. This indicates that the African horned cucumber fruit provides over 100% of the daily magnesium essential for human beings. Moreover, the results of this study may suggest that the consumption of African horned cucumber fruit cultivated under greenhouse and organic fertilisers may aid in the prevention of conditions such as muscle cramps, chronic fatigue, severe headaches, and irregular heartbeat, all of which are indicative of insufficient magnesium intake in the human diet (Shen et al., 2004; Yang et al., 2025).

Concerning the phosphorus content, the study's results showed that it varied between 175 and 573 mg/100g DW. Furthermore, the results demonstrate that the phosphorus content was reduced from 573 to 175 mg/100g DW in the treatment combination of shade net and control (without fertiliser), while it was increased from 175 to 573 mg/100g DW in the treatment combination of shade net and chemical fertiliser. The accumulation of phosphorus in plants is directly influenced by climatic conditions such as temperature, according to (Mou et al., 2020).

In this study, the variation between the maximum temperature of the greenhouse (28 °C) and the shade net (30.8 °C) was 2.8 °C, while the variation between the phosphorus ratio of chemical fertiliser (7.3) and organic fertiliser (4) was 3.3%. Phosphorus, as a mineral, is quite mobile yet it becomes constrained when temperatures decrease. The high rate of transpiration stemmed from the increased temperature in the shade net environment (30.8 °C) and the phosphorus-rich soil with a 7.3 ratio, likely to have led to an increase in phosphorus content in the fruits produced under this treatment combination, in contrast to the fruits grown in a similar environment without fertiliser (control), where plants might have depleted the phosphorus in the soil due to an inability to satisfy the transpiration demand caused by the elevated temperature, with no fertiliser to replenish it in the soil. These observations agree with the findings of (Singh et al., 2018) and (Maluleke et al., 2021), who noted discrepancies in the phosphorus content of fruits produced in differing climatic environments and fertiliser regimes.

In respect of human health and nutrition, phosphorus is vital because it is required for the development and maintenance of healthy bones and teeth, facilitating energy production, and constituting the backbone of DNA and RNA (Takeda et al., 2004). Phosphorus, an essential mineral, is necessary for several bodily functions, including building and maintaining strong teeth and bones, producing energy, and maintenance (Chenard et al., 2005). The difference between the superior phosphorus content of the African horned cucumber fruit (573.7), harvested from plants grown in shade net and chemical fertiliser, and the average recommended daily consumption (369.8 mg) was 209.9 mg. This could mean that the African horned cucumber grown from the treatment combination of shade net and chemical fertiliser could potentially contribute above 100% of phosphorus required by human beings daily. Additionally, values obtained from this study imply that consumption of the African horned cucumber fruit grown under the treatment combination of shade net and chemical fertiliser could assist in curbing conditions such as muscle weakness, constant bone pain, and a poor respiratory system, all of which are symptom conditions of low phosphorus intake in the human diet (Chenard et al., 2005; Hannoufa and Hossain, 2012).

4.3 Micro-minerals

Figure 3 illustrates the micro-minerals content of African horned cucumber fruit grown in distinct environment and fertiliser types. The study's results reveal a substantial ($P \leq 0.05$) difference in the beta-carotene, copper, iron, and zinc content of African horned cucumber fruit cultivated under different fertilisers and conditions. In respect of beta-carotene content (Figure 3A), the study's results varied between 0.5 and 1.3 mg/100 g DW. Moreover, the study's results delineate that the treatment combination of greenhouse and control (without fertiliser) reduced beta-carotene from 1.3 to 0.5 mg/100g DW, whereas the treatment combination of shade and chemical fertiliser increased it from 0.5 to 1.3 m/100g DW. It has been demonstrated by authors such as (Eggersdorfer and Wyss, 2018), that temperature combined with fertilisers has a major effect on beta-carotene accumulation in plants.

In this study, the variation between the maximum temperature of the greenhouse (28 °C) and that of the shade net (30.8 °C) was 2.8 °C, while the nitrogen ratio variation between the chemical (4.9) and organic (6) fertilisers was 1.1%. Consequently, he heightened temperature in the shaded net environment (30.8 °C) along with the nitrogen-enriched fertiliser may have directly contributed to an augmentation of beta-carotene in fruits cultivated under this combination, as the accumulation of this compound in plants and fruits was regulated by the methylerythritol phosphate pathway and the carotenoid biosynthetic pathway, which are typically activated by these factors, serving as significant environmental regulators responsible for metabolic shifts that induce changes in enzymatic activity and cellular structure. Unlike the plants in the greenhouse environment without fertiliser, resulting in reduced beta-carotene concentration, the stable temperature might not have necessitated any metabolic adjustments in the plants due to the temperate conditions. These discoveries are consistent with those of (Dasgan et al., 2021), who reported fluctuations in tomato fruit subjected to diverse temperature stress intensities.

In human health and nutrition, beta-carotene plays a crucial role, as it is a potent antioxidant, and its intake through fruits is linked to various health benefits, including vision, immune function, and potentially a reduced risk of certain chronic diseases (Ma et al., 2005). The difference between the greatest beta-carotene concentration (1.3) found in fruits produced from plants cultivated with a combination of shade net and chemical fertiliser and the ARDI (4.5 mg) was 3.2 mg. This implies that the African horned cucumber fruit grown under the treatment combination of shade net and chemical fertiliser may potentially contribute about 28% beta-carotene required by human beings daily. Furthermore, research findings may suggest that consuming the African horned cucumber fruit cultivated under the combined conditions of shade

netting and chemical fertiliser could help to mitigate ailments such as visual impairment, dermatological problems, and heightened susceptibility to infections – all of which are indicative of insufficient beta-carotene levels in human health.

For copper content (Figure 3B), the study's results show that it ranged from 1.3 to 2.6 mg/100g DW. Furthermore, in comparison to other treatments, results indicate that the treatment combination of greenhouse and control resulted in lower copper content (1.3 mg/100g DW). Super copper content (2.6) was observed under the treatment combination of shade net and chemical fertiliser when compared to other treatments. It is well established that plants absorb copper through their roots, and phosphorus-rich fertilisers facilitate this absorption by enhancing copper's bioavailability in soil, reducing rhizosphere pH to improve solubility, and readily absorbable complexes (Bouazizi et al., 2010).

For this investigation, the phosphorus content variation between chemical (8.8) and organic (4.8) fertilisers was 4mg, indicating a 54% variation, while the light intensity variation between the greenhouse (1093.6) and the shade net (1452.6) was 359 lux, indicating a 75.3% difference and the temperature variation between the greenhouse (28) and the shade net (30.8) as 2.8 °C. Consequently, the combination of elevated temperatures in the shade net (30.8 °C) and adequate phosphorus levels may have contributed to heightened metabolic activity, root development, and transpiration rates, which typically expedite mass flow and enhance transporter efficiency, thereby improving copper absorption in fruits subjected to this treatment. In contrast to the treatment involving a greenhouse environment at 28 °C without fertiliser, which may have led to diminished copper levels in fruits due to low soil temperatures hindering root respiration and membrane fluidity, thereby considerably impeding the transport mechanisms in the plant's roots and organs. These findings are consistent with those of Léchaudel et al. (2013), who found that environmental variables like temperature and light significantly affected a plant's ability to absorb and accumulate diverse compounds, consequently impacting its physiological performance.

In respect of human health and nutrition, copper is a vital trace mineral that is necessary for energy production, iron metabolism, collagen formation, and immune system function (Binesh and Venkatachalam, 2024). It also serves as a cofactor for enzymes that regulate antioxidants and neurotransmitters (Bost et al., 2016). In this study, the difference between the highest copper content (2.6) from fruit grown under the treatment combination (shade net and chemical fertilisers) and the ARDI (1.1 mg) was 1.5 mg. Therefore, the findings of this study could suggest that African horned cucumber fruit grown under a treatment combination of shade net and chemical fertiliser could provide more than 100% of the copper required by human beings daily. Furthermore, the consumption of African horned cucumber, grown under the combination of shade net and chemical fertiliser, may help to alleviate conditions such as chronic fatigue, weakened immune response, and compromised bone health, which are indicative of inadequate copper levels in the human diet (Altarelli et al., 2019).

Regarding iron content (Figure 3C), the results indicate a range of 3.6 to 11.5 mg/100g DW. Furthermore, the study's findings indicate that the combination of greenhouse treatment and control (without fertiliser) decreased the iron level from 11.5 to 3.6 mg/100g DW, whereas the combination of shade net and chemical fertiliser elevated it from 3.6 to 11.5 mg/100g DW. The combination of elevated root-zone temperature and soil fertility influences iron uptake and accumulation considerably (Morrissey and Guerinot, 2009; Baghour et al., 2016). In this study, the variation between the maximum temperature of the greenhouse (28 °C) and the shade net (30.8 °C) was 2.8 °C, which varied by a reasonable margin. Therefore, the heightened temperature in the shaded net environment (30.8 °C) may have directly contributed to the increased iron concentration in fruits cultivated in this environment, as elevated root-zone temperatures facilitate optimal iron translocation and enhance its uptake from soil to plant roots and other organs, including fruits. This was in contrast to the greenhouse environment (28 °C) with no fertiliser, where the lower temperature may have hindered iron mobility in the plant roots, resulting in reduced iron content in fruits grown under this treatment combination relative to others. These observations are consistent with the findings of (Baghour et al., 2016), who reported that a rise in root-zone temperature correlated with elevated iron content in a potato crop and its organs.

Iron is essential for human health and nutrition, primarily because of its critical role in oxygen delivery through haemoglobin in red blood cells (Siddiqui and Siddiqui, 2008). It also facilitates other physiological functions, including energy metabolism, immune response, and cognitive function (Coad and Pedley, 2014). The disparity between the maximum iron concentration (11.5 mg) in the African horned cucumber fruit cultivated under the treatment combination of shade net and chemical fertiliser and the average required daily consumption (15.2 mg) was 3.7 mg. This indicates that the African horned cucumber fruit cultivated under the combined treatment of shade net and chemical fertiliser may provide around 75% of the daily iron required for human beings. This study suggests that consuming African horned cucumber cultivated with a combination of shade net and chemical fertiliser may help to alleviate conditions such as chronic fatigue, respiratory issues, and compromised immune function, which are symptoms linked to insufficient iron intake in the human diet (Gupta et al., 2016; Wang et al., 2016).

Regarding zinc content (Figure 3D), the study's results show that it ranged from 7.6 to 25 mg/100g DW. Additionally, the results show that the treatment combination of greenhouse and control (without fertiliser) reduced the zinc content from 25.3 to 7.6 mg/100g DW, whereas the treatment combination of shade net and chemical fertiliser increased it from 7.6 to 25.3 mg/100g DW. Temperature is a known environmental factor that influences zinc accumulation in plants (Chasapis et al., 2012). According to research, rising temperatures cause plants to absorb and accumulate more zinc; however, the effect varies depending on the plant type and environmental conditions (Gibson, 2012).

In this study, there was a 2.8 °C difference between the highest temperature of the shade net (30.8 °C) and that of the greenhouse (28 °C), which varied by a noticeable margin. The heightened temperature in the shade net environment may have favourably influenced the rise in root-zone temperature and transpiration rate, thereby establishing optimal conditions for zinc translocation via

phloem remobilisation, which depends on water movement, facilitating nutrient transfer from leaves to fruit, resulting in elevated zinc content under this environment, in contrast to the greenhouse setting (28 °C) where the temperate conditions may have impeded root metabolism, obstructing zinc diffusion and its absorption by the plant and its organs, including fruits. These findings align with the observations of (Li et al., 2023), who noted that an increase in the root zone corresponded with a rise in zinc levels in the cucumber plant and its organs.

In human health and nutrition, zinc plays a crucial role in serving as a cofactor for numerous enzymes and facilitating a variety of physiological activities (Prasad, 2017). It is crucial for immune system functionality, DNA and protein synthesis, growth and development, and wound healing (Moyo et al., 2018). The variation between the highest zinc content (25.3 mg) of the African horned cucumber fruit grown under the treatment combination of shade net environment and chemical fertiliser and ARDI (9.1) was 16.3 mg. Therefore, the study's findings may imply that the African horned cucumber fruit grown under the treatment combination of shade net and chemical fertiliser may contribute 2.5 times of the zinc human beings require daily. In addition, the findings may suggest that consumption of the African horned cucumber fruit grown under the treatment combination of shade net environment and chemical fertiliser may assist in curbing conditions such as constant diarrhoea, slow growth, loss of appetite and impaired immune system, all of which are symptoms of low zinc content in human health and nutrition (Stiles et al., 2024).

4.4 Correlation findings

The strong patterns revealed in the Pearson correlation analysis offer significant insights into the biochemical responses of African horned cucumber under the imposed experimental conditions (greenhouse and shade net). The very strong negative associations linking the critical variable with sharp declines in beta-carotene ($r = -0.85$, $p < 0.01$), vitamin C ($r = -0.88$, $p < 0.01$), and multiple macro- and micronutrients, including calcium ($r = -0.89$, $p < 0.01$), sodium ($r = -0.98$, $p < 0.01$), phosphorus ($r = -0.79$, $p < 0.05$), magnesium ($r = -0.89$, $p < 0.01$), iron ($r = -0.78$, $p < 0.05$), and zinc ($r = -0.93$, $p < 0.05$) as shown in Figure 3, suggest that increases in this variable disrupt central metabolic pathways and exacerbate nutrient–nutrient antagonisms. Such disruptions ultimately reduce the stability, availability, and accumulation of essential antioxidants and minerals in plant tissue, a pattern consistent with stress-induced oxidative pressure and competitive ion interactions reported across plant systems (e.g., micronutrient cross-talk and redox-linked enzyme systems) (García-Caparrós et al., 2021; Fan et al., 2021; Zhang et al., 2022).

These findings align with established evidence that heightened physiological or metabolic stress accelerates antioxidant depletion and intensifies competition among nutrients within tightly regulated redox and enzymatic networks, most notably the ascorbate–glutathione (AsA–GSH) cycle, which coordinates detoxification and redox signalling in chloroplasts and other compartments. The depletion of non-enzymatic antioxidants (ascorbate, carotenoids, and tocopherols) under stress has been broadly documented and mechanistically linked to increased production of reactive oxygen species (ROS) and homeostatic imbalance (Hasanuzzaman et al., 2019; Abdulfatah, 2022; Mishra et al., 2023; Foyer and Kunert, 2024).

Conversely, the strong positive correlation observed between the variable and copper ($r = 0.79$, $p < 0.01$) highlights a divergent mineral response trajectory (Figure 5). Numerous studies have shown that Cu often accumulates or is regulated distinctly under stress, and its interactions with Zn and Fe are frequently antagonistic at the uptake and translocation levels, resulting in patterns that can suppress Fe and Zn movement to shoots and shift redox enzyme priorities. This is compatible with the very strong inverse relationships observed between Cu and several nutrients (e.g., Zn, Ca, and P). Together, these contrasting correlation patterns emphasise the complexity of nutrient interactions in plant systems and indicate that shifts in a single influential variable can reorganise

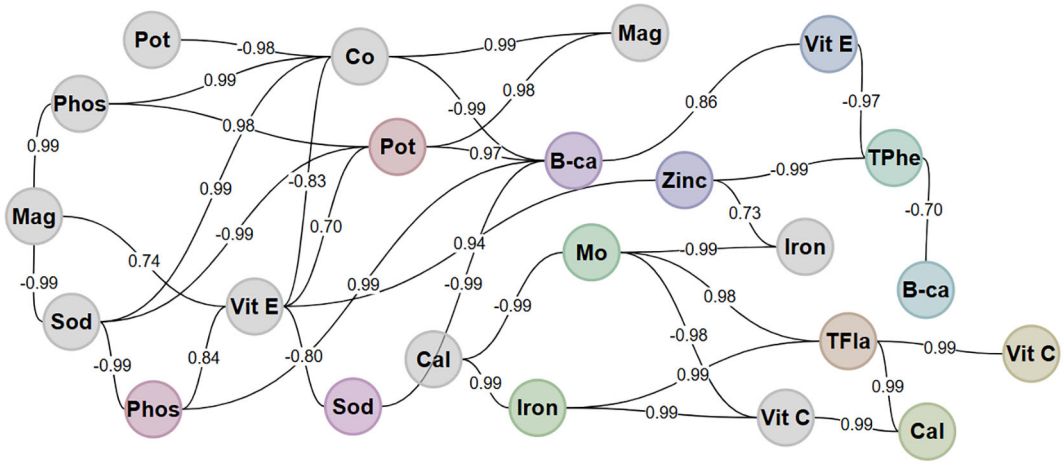


FIGURE 5
TFla vs Vit C, Cal, Iron, Mo; TPhe vs B-ca, Vit E, Zinc; B-ca vs Vit E, Sod, Phos, Pot, Co; Vit C vs Cal, Iron, Mo; Vit E vs Sod, Phos, Mag, Pot, Co, Zinc; Cal vs Iron, Mo; Sod vs Phos, Mag, Pot, Co; Phos vs Mag, Pot, Co; Mag vs Pot, Co; Pot vs Co; Iron vs Mo; Iron vs Zinc.

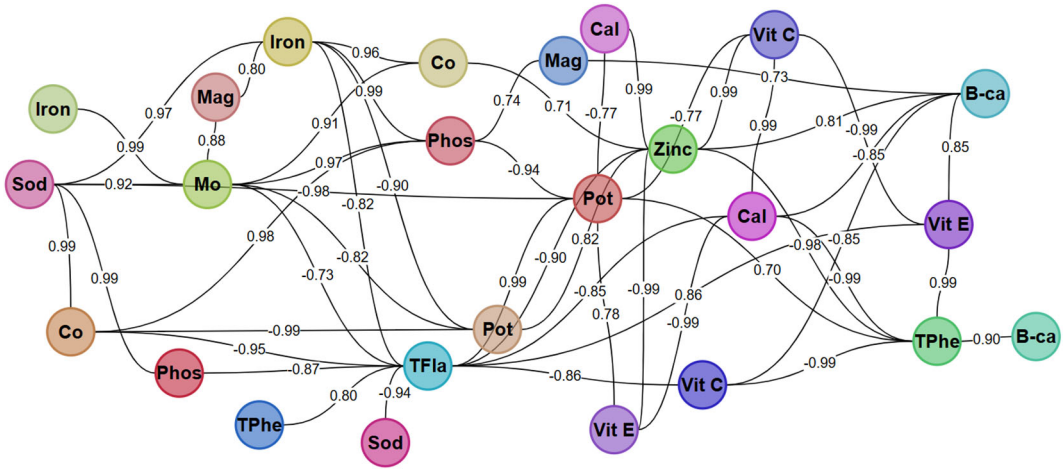


FIGURE 6
TFla vs TPhe Vit C, Vit E, Cal, Sod, Phos, Pot, Co, Iron, Mo, Zinc; TPhe vs B-ca, Vit C, Vit E, Cal, Pot, Zinc; B-ca vs Vit C, Vit E, Cal, Mag, Zinc; Vit C vs Vit E, Cal, Pot, Zinc; Vit E vs Cal, Pot, Zinc; Cal vs Pot, Zinc; Sod vs Phos, Pot, Co, Iron, Mo; Phos vs Mag, Pot, Co, Iron, Mo; Mag vs Iron, Mo; Pot vs Co, Iron, Mo, Zinc; Co vs Iron, Mo, Zinc; Iron vs Mo.

metabolic priorities with cascading effects on nutrient retention, redistribution, and biochemical stability, which are core themes in modern reviews of macro–micro cross talk (Gong et al., 2020; Fan et al., 2021; Kumar et al., 2021; Liščáková et al., 2022).

Vitamin C was very strongly and positively associated with calcium ($r = 0.99$, $p < 0.01$), sodium ($r = 0.93$, $p < 0.05$), phosphorus ($r = 0.99$, $p < 0.05$), and zinc ($r = 0.99$, $p < 0.05$), and was strongly negatively associated with copper ($r = -0.98$, $p < 0.01$), as shown in Figure 6. This pattern reflects the centrality of ascorbate in the AsA–GSH cycle and its sensitivity to redox-active metals; excessive Cu is known to disrupt Zn and Fe homeostasis and increase ROS, which elevates ascorbate turnover. Vitamin E showed very strong positive correlations with magnesium ($r = 0.93$, $p < 0.01$), potassium ($r = 0.93$, $p < 0.01$), iron ($r = 0.99$, $p < 0.01$), and molybdenum ($r = 0.89$, $p < 0.01$). These associations are consistent with vitamin E's membrane-protective role in photosynthetic tissues, where Mg and Fe are pivotal for chlorophyll structure and electron transport, K^+ supports photosynthetic and redox homeostasis, and Mo contributes via nitrate reductase and redox enzymes, factors tied to tocopherol dynamics under stress (García-Caparrós et al., 2021; Niu et al., 2022; Ali et al., 2021; Therby-Vale et al., 2022; Gupta et al., 2024; Hosseini Pouya et al., 2026).

Mineral networks and antagonisms were also investigated, as Ca was strongly and positively correlated with Na ($r = 0.93$, $p < 0.01$), P ($r = 0.98$, $p < 0.01$), and Zn ($r = 0.99$, $p < 0.05$), and very strongly negatively correlated with Cu ($r = -0.98$, $p < 0.01$), as depicted in Figure 7. Ca often conditions membrane stability and signalling and can modulate ion transport; strong Ca–Zn synergy and Ca–Cu antagonism have been reported in disease and nutritional contexts. Na displayed strong to very strong positive associations with P ($r = 0.85$, $p < 0.05$), Mg ($r = 0.84$, $p < 0.05$), Fe ($r = 0.71$, $p < 0.05$), and a strong negative association with Cu ($r = -0.85$, $p < 0.01$); it was also strongly correlated with the additional variable ($r = 0.97$, $p < 0.05$). Although Na^+ is not essential for most glycophytes, in

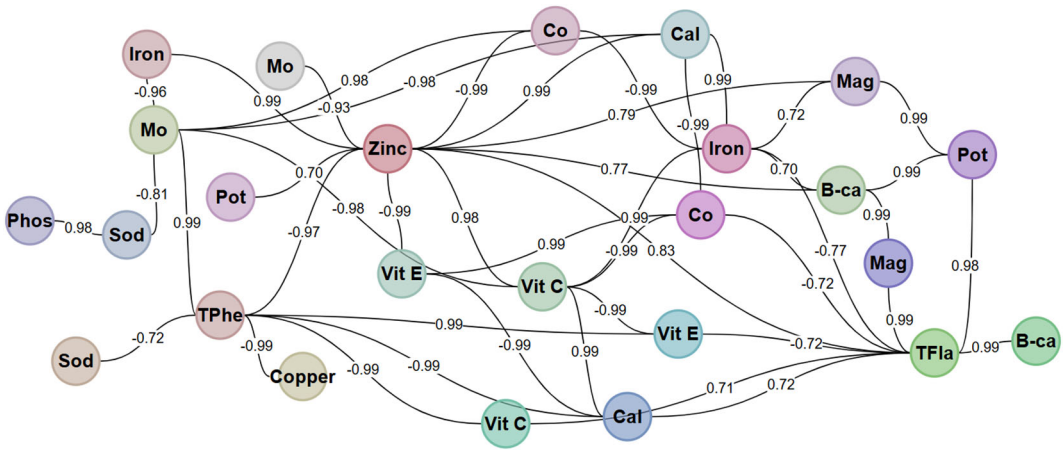


FIGURE 7
TFla vs B-ca, Vit C, Vit E, Cal, Mag, Pot, Co, Iron, Zinc, Vit C; TPhe vs Vit E, Cal, Sod, Copper, Mo, Zinc; B-ca vs Mag, Pot, Iron, Zinc; Vit C vs Vit E, Cal, Co, Iron, Mo, Zinc; Vit E vs Cal, Co, Zinc; Cal vs Co, Iron, Mo, Zinc; Sod vs Phos, Mo; Mag vs Pot, Iron, Zinc; Pot vs Zinc; Co vs Iron, Mo, Zinc, Iron vs Mo, Zinc; Mo vs Zinc.

stress contexts, it reshapes ion balance and interacts with K^+/Ca^{2+} signalling; halophyte research and Na^+ flux regulation have highlighted how sodium levels can restructure nutrient flows and oxidative status compatible with these broad linkages (Ali and Yun, 2017; Shahid et al., 2020; Lorenzetti et al., 2021; Maathuis, 2014).

Phosphorus correlated very strongly with zinc ($r = 0.96$, $p < 0.01$) and very strongly negatively with copper ($r = -0.99$, $p < 0.01$), as shown in Figure 7. Although the data show a positive P–Zn correlation, agronomic literature repeatedly documents a context dependent P–Zn antagonism, especially under high P supply via precipitation/complexation and mycorrhiza mediated effects. This underscores that correlation signs can flip with background supply and tissue partitioning. Magnesium was strongly correlated with iron ($r = 0.98$, $p < 0.01$) and strongly correlated with potassium ($r = 0.72$, $p < 0.05$) (Figure 5). Given Mg's central position in chlorophyll and Fe's role in photosynthetic electron transport, tight Mg–Fe co-variation is common; K^+ further supports photosynthesis and redox balance mechanistically consistent with the observed Mg–K linkage. Potassium was very strongly positively correlated with iron ($r = 0.85$, $p < 0.05$), aligning with evidence that K^+ improves photosynthesis, ion homeostasis, and antioxidant status, thereby sustaining Fe dependent photosynthetic machinery under stress (Ragel et al., 2019; Xie et al., 2019; Nath et al., 2024; Hosseini Pouya et al., 2026; Therby-Vale et al., 2022; Zhu et al., 2025).

Copper and zinc were strongly and inversely related ($r = -0.96$, $p < 0.01$), reinforcing their well-established antagonistic interaction in uptake and translocation, as documented from classic hydroponic and soil studies to recent reviews and agronomic trials. Since zinc can enhance photosynthetic efficiency and antioxidant enzymes in cereals, reflecting complementary roles in nitrate metabolism, redox enzymes, and metal homeostasis (Liu et al., 2019; Liščáková et al., 2022).

5 Conclusion

This study explored the combined impact of the growing environment and fertiliser type on the nutritional content of the African horned cucumber fruit. The fruit's potential impact on human health and nutrition was assessed by comparing its nutritional composition to the ARDI. The investigation disclosed notable findings concerning the nutritional and mineral composition of the fruit in relation to the treatments applied. The biochemical constituents, comprising total flavonoids, total phenols, and vitamins C and E, increased under the combined treatment of greenhouse conditions and chemical fertilisers. In contrast, mineral elements such as calcium, phosphorus, beta-carotene, iron, and zinc were much more abundant under the combined treatment of a shade net environment and chemical fertiliser compared to other treatments. As a result, the nutritional data provided in this study could serve as baseline information for future crop improvement efforts aimed at better understanding crop responses to the combination of growing environment and fertiliser use. This will assist in the development of varieties that respond favourably to growing conditions and fertiliser application, thereby expediting the commercialisation of the crop, which will contribute to achieving SDGs such as SDG2 (Zero Hunger), promoting universal access to nutrient-dense food for all communities, irrespective of their economic status.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The experiment was conducted strictly in compliance with the regulations of Unisa's College of Agriculture and Environmental Sciences Research and Higher Degree Committee (ethical number reference: 2022/CAES_HREC/104). The protocol was approved by Unisa-Caes Health Research Ethics Committee in accordance with the local and international guidelines and regulations.

Author contributions

NM: Writing – review & editing, Investigation, Methodology, Project administration, Writing – original draft, Formal analysis, Visualization. UO: Validation, Software, Resources, Writing – review & editing, Writing – original draft. SF: Formal analysis, Methodology, Writing – review & editing, Supervision, Writing – original draft, Resources. RM: Supervision, Writing – original draft, Writing – review & editing, Visualization, Formal analysis. MM: Validation, Methodology, Writing – review & editing, Conceptualization, Resources, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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